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Project 4.5

AIR PRESSURES FROM A DEEP UNDERWATER BURST

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No. 146 of 210 copies, Series A

Report to the Scientific Director

(16) (7) NA (9) NA

AIR PRESSURES FROM A DEEP UNDERWATER BURST

(10) ~~By~~

by M. L. Merritt

(12) 20p. (13) NA 14 - 17 NA (20) S-RD

(21) WT-1035 supersedes ITR-1083

Approved by: H. E. LENANDER
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Albuquerque, New Mexico
(11) Dec~~ember 1955~~,

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ABSTRACT

Project 4.5 was to study the danger to aircraft from air pressures resulting from a deep underwater nuclear explosion, and to this end measurements were planned from the surface to a height of 500 ft and out to 6000 ft from surface zero. Bad weather forced abandonment of all but two measurements, surface pressures at 0 and 5500 ft. These data confirm that acoustic coupling can predict peak air pressures at the surface but not later pressures. From Project 4.5 results and data from experiments on high explosives, predictions are made of air pressures to be expected from Wigwam type weapons.

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AIR PRESSURES FROM A DEEP UNDERWATER BURST

1 OBJECTIVES

The purpose of Project 4.5 of Operation Wigwam was to measure air pressures from a deep underwater nuclear explosion at the surface and at altitudes approaching those which would be used by a delivery aircraft. In particular it was desired:

1. To determine the coupling of the water and the air shock, and
2. To determine the attenuation of the shock wave with altitude.

2 BACKGROUND AND THEORY

A secondary but important consideration in any proposed use of nuclear weapons is that the delivery aircraft should escape unharmed by its cargo. An underwater explosion is dangerous to an airplane because of the resulting shock wave and because of water thrown up into the air. In this project we deal only with the shock in air; surface effects are considered by Project 1.5.[1]

The problem of what the air pressures from an underwater burst will be is not as simple as has sometimes been assumed. Underwater shock pressures can be estimated from empirical formulas[2,3] and were measured at Wigwam directly by Projects 1.2,[4] 1.2.1,[5] and 1.3[6] and indirectly by Project 4.4.[7] The magnitude of a shock transmitted from water into air can be estimated using acoustic theory,[8,9] but this method estimates only the peak overpressure without specifying the subsequent decay. Finally, it is not certain how the wave will propagate and decay in the air away from the surface.

Transmission of a pressure wave from water into air can be described acoustically:[8]

$$\frac{P_a}{P_w} \doteq \frac{2\,\rho_a c_a \cos\phi_w}{\rho_w c_w \cos\phi_a} \tag{1}$$

where P_a and P_w are peak overpressures in air and water, respectively, ρ_a and ρ_w are densities of air and water, c_a and c_w are velocities of sound, and ϕ_w and ϕ_a are angles from the normal of incidence and transmission. The angles ϕ_w and ϕ_a are related by Snell's law:

$$\frac{\sin\phi_w}{\sin\phi_a} = \frac{c_w}{c_a} \tag{2}$$

These expressions apply only to the initial overpressure. The time scale of the air pressure wave is longer than that of the water wave because water thrown up in the dome maintains air pressures while pressures in the water below are falling. Although experiments show this effect, no descriptive theory of it appears to exist.

In acoustics, overpressure in air falls off inversely as the distance from the apparent source of the explosion, modified by the vertical gradient of density and velocity of sound in the atmosphere. The overpressure varies as:

$$P = \frac{k\sqrt{\rho c}}{r} \tag{3}$$

The physical reason for this is that the pressure wave diverges as it travels away from its source so that its energy is spread over a larger area. In shock waves another factor causes the peak overpressure to decrease faster than acoustically. This factor is the degradation of the strength of the shock front as a rarefaction from behind catches up with the front itself. In the air pressure wave from an underwater explosion, a third factor enters, crossfeed between parts of the wave not at the same pressure. For weak shocks, these several effects can be consolidated into the one differential equation

$$\frac{1}{Z}\frac{dZ}{dr} = -\frac{1}{r} - \frac{3}{7}\frac{Z}{c\theta} - \frac{7}{10}\frac{1}{Zr\sin\phi}\frac{\partial}{\partial\phi}(\bar{U}\sin\phi) \tag{4}$$

where Z is the ratio $\Delta P/P_0$ of the overpressure to the pressure in front of the shock, r is the distance to the center of curvature of the shock front, θ is the time constant of the shock defined by the expression

$$\frac{1}{\theta} = -\frac{1}{Z}\left(\frac{\partial Z}{\partial t}\right)_r \tag{5}$$

and $\bar{U}$ is the particle velocity in the wave in the direction ϕ perpendicular to r, normalized by dividing by the ambient velocity of sound, c_0. All quantities are to be evaluated in Eulerian coordinates at the shock front. The first term on the right of Eq. 4 represents the divergence of the wave; the second, dissipation at the front; and the third, crossfeed, or the influence of neighboring parts of the wave not at the same pressure.

For spherical symmetry, i.e., no crossfeed, there exists an integration of Eq. 4.

$$\frac{Z}{Z_0} = \frac{r_0}{r}\left[1 + \frac{3(m+1)}{7}\frac{Z_0 r_0}{c\theta_0}\ln\frac{r}{r_0}\right]^{-[1/(m+1)]} \tag{6}$$

where m is a shape factor needed to describe how the time constant changes:

$$\frac{dc\theta}{dr} = \frac{3mZ}{7} \tag{7}$$

Crossfeed appears in Eq. 7 as well as in Eq. 4. The effect in Eq. 4 is the result of adjacent parts of the shock front traveling at different speeds because they are of different strengths. The effect which makes itself felt as a damping time constant in Eq. 7 is the result of crossflow being set up by pressure gradients behind the front and the resulting rarefactions or compressions reaching the front. The combined result of these several effects is included in the expression

$$\frac{Z}{Z_0} = \frac{r_0}{r}\left(1 + \frac{3}{7}\frac{Z_0 r_0}{c\theta_0}\ln\frac{r}{r_0}\right)^{-1}\left[1 + \frac{3}{7}Z_0\left(\frac{r - r_0}{d}\right)^2\right]^{-1} \tag{8}$$

valid near the vertical axis. It is to be noted that the shape factor has been set equal to zero: changes in the time constant caused by signals from behind the front and by crossfeed are in opposite directions and are roughly equal. The last term on the right of Eq. 8 is the residual effect of unequal velocities of different parts of the shock front. Each of these several effects makes the overpressure decrease faster than acoustically.

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3 RELATED EXPERIMENTS

The Waterways Experiment Station (WES), Vicksburg, Miss., in conjunction with the Naval Ordnance Laboratory (NOL), has made an extensive study of air pressures from underwater bursts of TNT.[12] The deepest of these bursts were of 32-lb spheres of TNT at depths of 16.22 ft, which corresponds by $W^{1/3}$ scaling to a depth of 1750 ft for 20 kt (4×10^7 lb) of TNT or to a depth of 2000 ft for 30 kt of TNT. The resulting data for this deepest burst are summarized in Fig. 1 and Table 1.

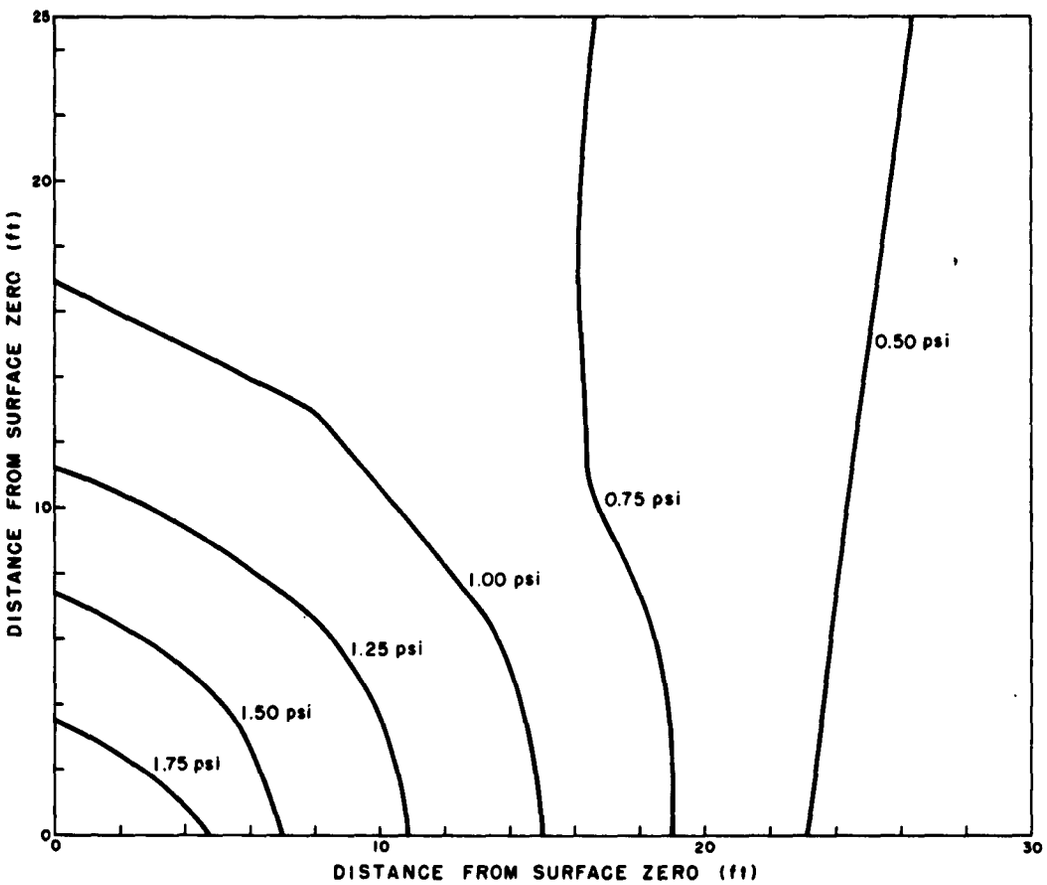

Fig. 1—Overpressures in air from the burst of 32 lb of TNT at a depth of 16.2 ft. Data obtained at WES.

These data can be used to test the theoretical ideas expressed above. In Table 2 the coupling factors (P_a/P_w) predicted by Eq. 1 are compared with those measured. As NOL says, "the agreement numerically is not satisfactory" (reference 12, p. 11). In every case except above surface zero the measured values are low.

The last column in Table 1 gives time constants determined from tracings of the original records. These indicate that the time scale of the air pressure wave was about 14 times as long as that of the underwater wave. If the water of the dome had acted as a perfect piston, the time constant of the resulting air pressure wave would be V_0/a, or of the order of seconds. It is obvious that the water did not act as a perfect piston.

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Table 1 — RESULTS OF AIR PRESSURE AND WATER SHOCK MEASUREMENTS
(Charge Depth = 16.22 ft; Charge Weight = 32 lb)

x*	y*	n†	ΔP‡	t_a§	θ¶
0	−1	4	4050	2.58	0.313
0	−0.5	3	3560	2.91	0.381
0	+0.5	8	1.98	3.13	4.92
0	1.0	4	1.63	3.64	4.31
0	4.0	5	1.8	6.11	5.64
0	6.0	2	1.6	7.96	5.04
0	6.67	4	1.55	8.58	5.80
0	10.0	4	1.25	11.28	4.77
0	12.0	2	1.35	12.96	5.08
0	16.22	4	0.98	16.96	4.81
0	20.0	4	1.05	20.52	4.18
0	25.0	4	1.05	24.37	5.87
5.0	1.0	2	1.7	3.80	4.68
8.1	−0.5	10	4050	3.30	0.365
8.1	+0.5	10	1.42	3.53	5.91
8.1	4.0	5	1.34	6.20	9.81
8.1	6.67	4	1.33	8.05	7.99
8.1	12.0	6	0.93	12.95	6.12
8.1	25.0	4	0.98	24.36	7.53
10.0	1.0	2	1.3	4.22	8.50
10.0	12.0	2	1.1	13.74	6.03
15.0	1.0	4	1.03	5.01	6.70
15.0	9.0	2	0.7	11.90	6.25
17.7	−16.2	14	3440	3.24	0.366
20.0	+1.0	1	0.6	5.97	4.70
24.3	−0.5	6	2380	5.58	0.381
24.3	+0.5	6	0.43	5.78	5.58
24.3	4.0	4	0.48	9.28	4.38
24.3	6.67	4	0.40	10.74	8.38
24.3	10.0	2	0.5	14.20	5.65
24.3	25.0	2	0.55	26.84	9.32
25.0	1.0	1	0.4	6.55	10.02
30.0	1.0	1	0.2	7.44	11.3
40.54	−0.5	1	1300	8.70	0.20
40.54	+0.5	7	0.24	8.90	4.46
56.77	+0.5	4	0.1	11.97	5.92

*x,y: Cartesian coordinates based on surface zero.
†n: number of measurements of ΔP.
‡ΔP: peak overpressure.
§t_a: arrival time from burst time.
¶θ: initial time constant.

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In Fig. 2 the experimental data over surface zero are compared with overpressures predicted acoustically and with those predicted by Eq. 8, assuming that the surface-level pressure is correct. For comparison a dashed line has been added which represents the best statistical fit to the data. These data indicate clearly that the air shock from an underwater explosion cannot be treated as an acoustic problem only.

It has been implied that WES data should be representative of the Wigwam shot because the scaled depths were roughly the same. On the other hand, there is at least one a priori reason to expect the WES data not to scale. The reasons for the nonlinear (nonacoustic) behavior of the air wave are crossfeed and the expansion behind the front. How important the latter effect is depends on the dome. But the dome cannot scale. The dome starts rising at a velocity which depends on the incident overpressure (and to a small extent on surface roughness) and is thereafter slowed down by gravity and air drag. And gravity does not scale. Both in the WES experiments and in Wigwam the initial upward rise of the water at surface zero was about 100 ft/sec. Because of gravity neither dome could rise more than about 150 ft. The scale factor between the two was 108; so the Wigwam dome had roughly 100 times the density of the other and should be a more effective piston. It should keep the overpressure positive relatively longer at Wigwam and make duration effects on peak pressures less. Peak overpressures at altitude should be greater than WES type data would indicate.

Table 2 — COUPLING FACTORS FROM WES DATA

Station	Theoretical	Experimental	Ratio
$x = 0$	5.4×10^{-4}	5.56 ± 0.73	0.97
$x = 8.1$	4.8×10^{-4}	3.51 ± 0.02	1.33
$x = 2.43$	3.0×10^{-4}	1.81 ± 0.12	1.66
$x = 40.5$	2.0×10^{-4}	$1.84 \pm ?$	1.09

4 EXPERIMENTAL PLANS AND OPERATION

Original plans for this project included measurements of free-air overpressure vs time at surface ranges of 0, 2300, 3900, and 6100 ft. These stations were represented in the tow line by the YC-473, the LCM-1A, the LCM-2A, and the YFNB-12, respectively. Measurements were to be made at heights of 50, 250, and 500 ft above the water except at the 2300-ft station, where a measurement at 50 ft only was to be made. Mooring lines of large helium-filled balloons of nylon-covered polyethylene were to be used to hold the gauges in place. Each balloon would supply a free lift of 2200 lb to support gauges, transmitters, and cables, and each was to be flown at an altitude of 650 ft.

The first three stations were expected to sink after the burst; therefore the data from these stations were to be telemetered by FM-FM radio to the USS Curtiss. Two transmitters for this purpose were to be hung 50 ft below each balloon, each housed in a waterproofed metal container and each pair with a quarter-wave ground-plane antenna mounted on top. Two gauges were to be mounted at each height of interest with electrical cables running from each gauge of a pair to a different transmitter, thus assuring complete information even should one transmitter fail.

The six transmitted signals were received at a trailer on the fantail of the USS Curtiss. The frequency-modulated signals were recorded directly on Ampex magnetic-tape recorders and were also discriminated and recorded on Consolidated oscillographs.

The 6100-ft station was expected to survive the detonation; therefore, at it, hard-wire telemetering was used, data being recorded on a magnetic-tape recorder and on a Midwest oscillograph.

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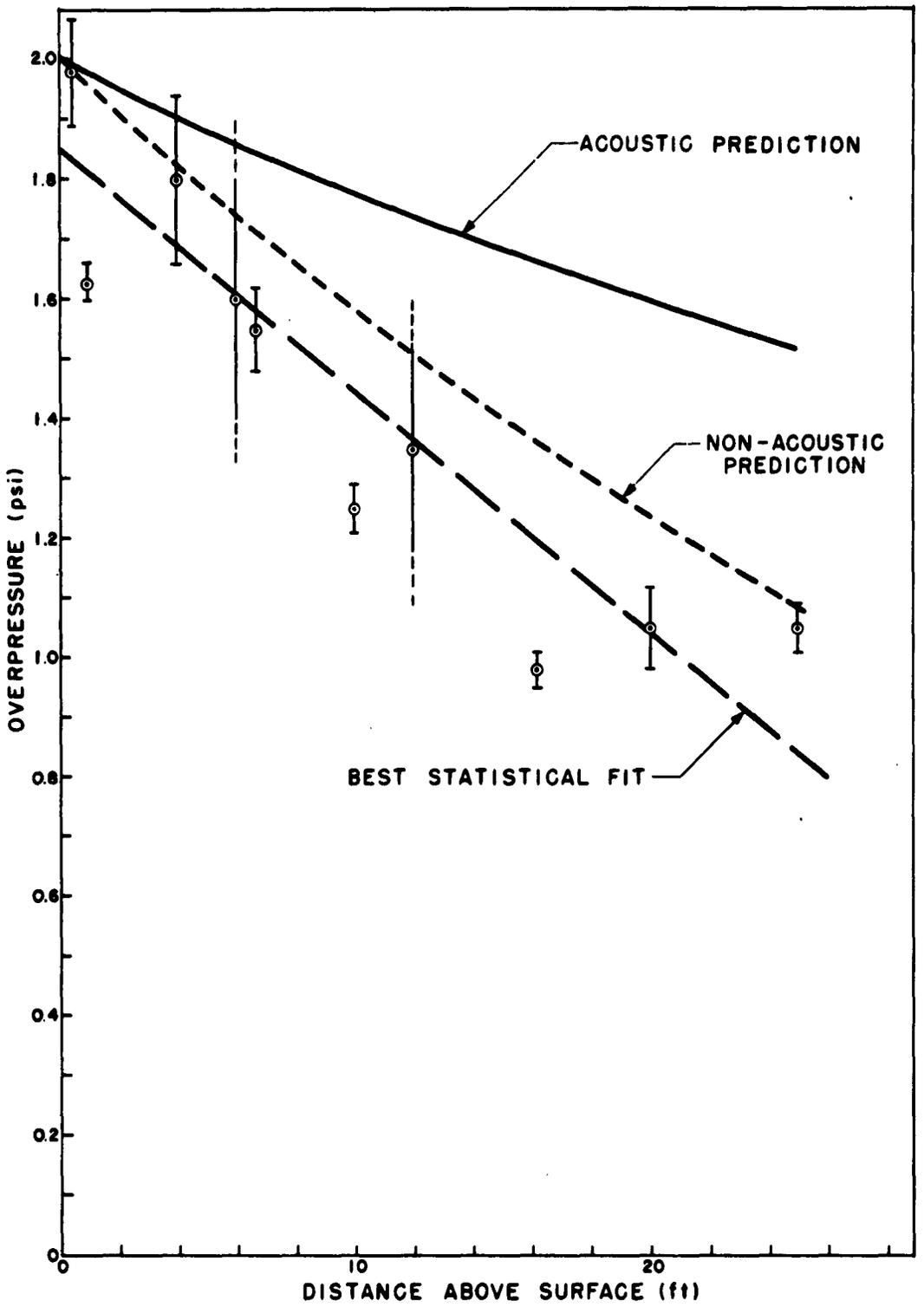

Fig. 2—Comparison of WES data with predictions.

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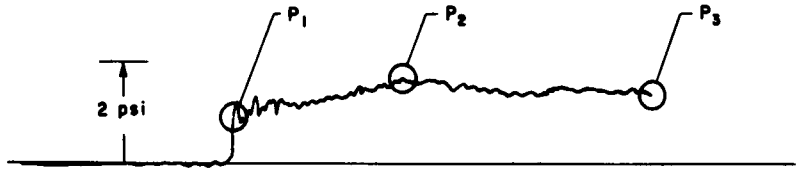
Pressure transducers used were the Wiancko twisted Bourdon-tube gauge and the Northam and Datran diaphragm type variable-reluctance gauges.

Four balloons were inflated and put into position on the tow line on D−2, but continuing high winds and rough seas prevented attaching the gauges and associated telemetering equipment to the mooring lines and raising them to altitude. The wind-buffeted balloons became a hazard to aircraft and to the equipment of other projects and had to be cut loose; measurements at altitude had to be abandoned.

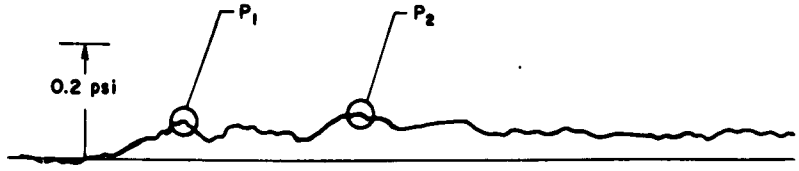
In an eleventh-hour attempt to salvage some information of value, gauges were installed on D−1 on the YC-473 and the YFNB-12 near the water surface. No such gauges could be installed on LCM's 1A and 2A because the tailgate of the USS Comstock broke and boats which were to have been used for transportation could not be removed from the well. On the YC all gauges were mounted on a steel framework welded to the deck so as to extend several feet out over the water and about 20 ft above it. Gauges were mounted on the YFNB at three different locations: two on the rail near the bow, two in the cable tub on the forecastle deck, and two tied to a boom on the helicopter deck. These gauges were about 24 ft from water level.

5 RESULTS AND DISCUSSION OF DATA

At both the YC and the YFNB there were several gauges and hence several overpressure-time records. Sample wave forms are shown in Fig. 3, and overpressures and times determined from these records are given in Table 3. This table includes all the few data obtained in Project 4.5.



Gage OMN, surface range 0 ft



Channel 4, surface range 5500 ft

Fig. 3—Sample wave forms.

Measurements of undersurface pressures were made at the YC by the Naval Research Laboratory (NRL) (Project 1.2.1) and indirectly by the Armour Research Foundation (ARF) (Project 4.4), and at the YFNB-12 by the Naval Ordnance Laboratory (NOL) (Project 1.2) and the Navy Electronics Laboratory (NEL) (Project 1.3). Their preliminary results are tabulated in Table 4. In this table are also given coupling factors (P_a / P_w) calculated from these data and acoustically from Eq. 1. Agreement is better than in the case of the WES data.

It was impossible to keep the gauges completely free from interference from the barge on which they were mounted. This effect is such as to delay the rise to maximum overpressure, but it should not affect that maximum by more than 5 per cent.

Only from surface zero measurements can a time constant be determined: it is about 430 msec, 15 times as long as the underwater time constant. This is very nearly the same ratio as

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Table 3—RESULTANT DATA, PROJECT 4.5

Surface Zero Station

	Gauge				Average
	OLD	OHD	OMN	OHN	
ΔP_1 (initial rise), psi	0.799	0.861	0.793	0.727	0.795 ± 0.055
ΔP_2 (max. pressure), psi	1.370	1.390	1.302	1.368	1.357 ± 0.038
ΔP_3 (final pressure), psi	1.23	1.33	1.12	1.18	1.214 ± 0.09
T_a (arrival time), msec	403.5	404.6	403.9	404.6	403.9
T_{rise} (time to max.), msec					29.8
T (duration of record), msec					75.3
θ (time constant), msec	445	1053	325	331	430 ± 320 − 130

5500-ft Station

	Gauge						Average
	1N	2W	3N	4W	5N	6W	
ΔP_1 (first max.), psi*		0.110		0.143		0.115	0.123 ±0.018
ΔP_2 (second max.), psi*	0.172	0.138		0.165		0.156	0.158 ±0.015
T_a (arrival time), msec	1182 ±5	1182	1182	1182	1182	1182	1182 ± 5
T_+ (positive duration), msec	207.0	256.0		195.3		160.0	204.6 ± 70

*Secondary signals observed at 4.0, 5.9, and 11.8 sec.

Table 4—COMPARISON OF MEASURED AND THEORETICAL COUPLING FACTORS

Station	Underwater pressure, psi	Air overpressure, psi	Coupling (experimental)	Coupling (theoretical)	Ratio
0 ft	Proj. 1.2 (NOL): 3000	1.36	4.55×10^{-4}	5.35×10^{-4}	1.18
	Proj. 1.2.1 (NRL): 3000	1.36	4.55×10^{-4}	5.35×10^{-4}	1.18
	Proj. 4.4 (ARF): 2960	1.36	4.60×10^{-4}	5.35×10^{-4}	1.16
5500 ft	Proj. 1.2 (NOL): 850	0.16	1.88×10^{-4}	1.85×10^{-4}	1.00
	Proj. 1.3 (NEL): 800–850	0.16	1.94×10^{-4}	1.88×10^{-4}	0.97

is inferred from WES data. Thus the Wigwam dome was only slightly more effective a piston than the dome in WES experiments.

Even after Wigwam the only large number of experimental data on overpressures in air from underwater bursts are the WES data. The evidence is that the water-to-air coupling was about the same at Wigwam as in the WES experiments. On the other hand, the deepest WES shot was not as deep scalewise as the Wigwam shot. These considerations mean that overpressures in air from Wigwam must be extrapolated from the WES data using a theoretical approach such as culminated in Eq. 8. The results of such an extrapolation are shown in Fig. 4.

Two items of digression are in order. First, two condensation cones over surface zero were observed.[1] These cones indicate that negative-phase overpressures were as large as 1 psi. However, this pressure is probably not dangerous to aircraft since it is gradually, not

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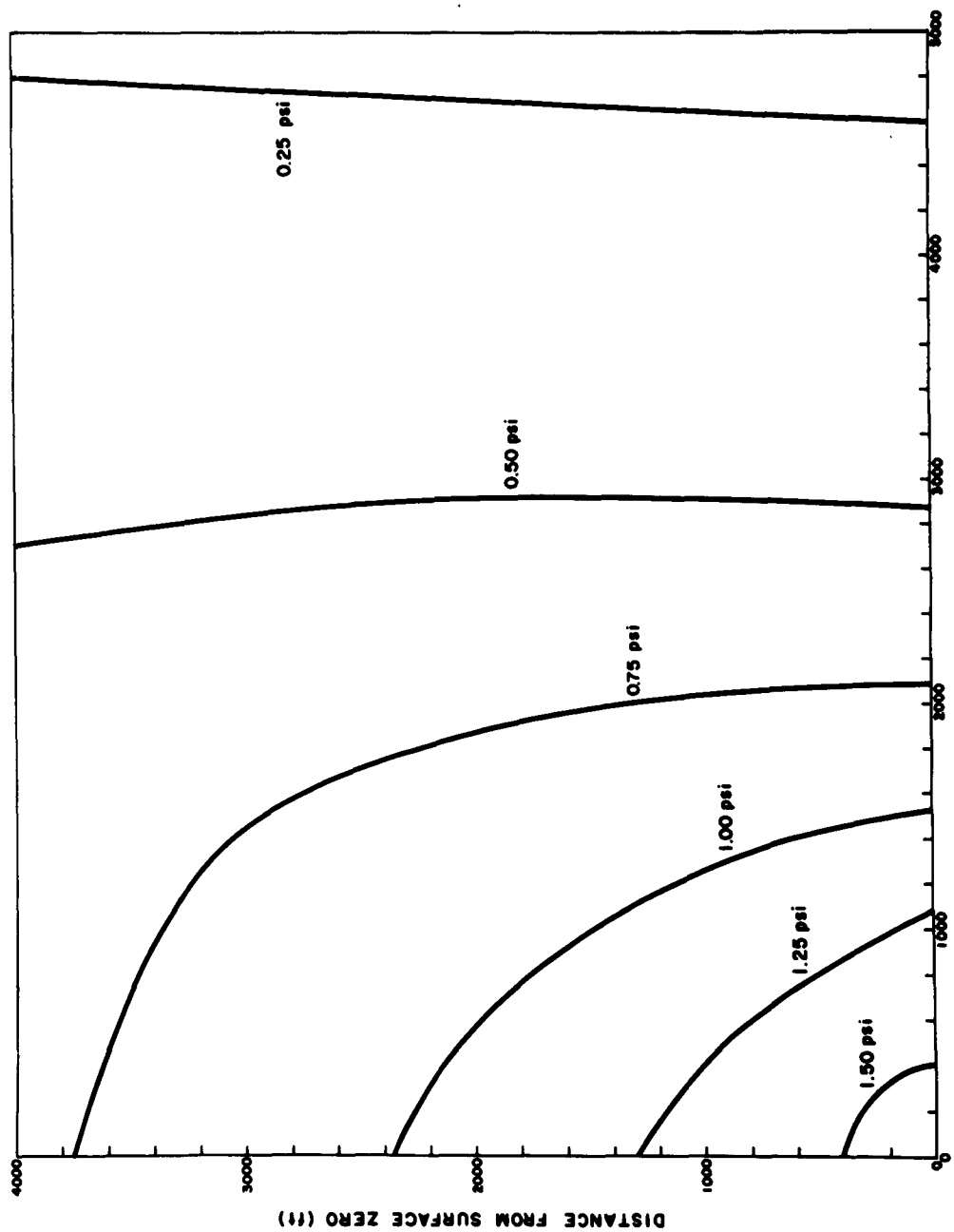

Fig. 4—Prediction of air pressures for a Wigwam type burst.

suddenly, applied. Second, gauges at the YFNB-12 recorded a number of secondary pressure signals. The most obvious of these were at 4.0, 5.9, and 11.8 sec. The first two of these correspond to the arrival of signals from the first bubble pulse and the signal reflected from the bottom. These later signals were not shocks, but wave trains of indeterminate character.

6 CONCLUSIONS AND RECOMMENDATIONS

Principally because of bad weather, only a few data were obtained in Project 4.5. These data, considered with theory and with high-explosives data, lead to these conclusions and recommendations:

1. The coupling of peak overpressures of water and air shock waves can be described acoustically using Eq. 1. Subsequent behavior cannot.
2. Propagation of the overpressure wave in air away from the surface cannot be described acoustically (Eq. 3).
3. For planning purposes, we recommend using overpressures in air scaled from WES data as presented in Fig. 4.
4. If any further underwater bursts are made, we recommend measuring air pressures from them, but not by using balloons unless better guarantees can be given about weather than at Wigwam. Particularly should pressure measurements be made if relatively shallower bursts are contemplated.

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Chief of Research and Development, D/A, Washington 25, D. C. ATTN: Special Weapons and Air Defense Division	2
Chief of Ordnance, D/A, Washington 25, D. C. ATTN: ORDTX-AR	3
Chief Signal Officer, D/A, P&O Division, Washington 25, D. C. ATTN: SIGOP	4–6
The Surgeon General, D/A, Washington 25, D. C. ATTN: Chief, R&D Division	7
Chief Chemical Officer, D/A, Washington 25, D. C.	8–9
The Quartermaster General, D/A, Washington 25, D. C. ATTN: Research and Development Div.	10
Chief of Engineers, D/A, Washington 25, D. C. ATTN: ENGNB	11–15
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Commanding General, Continental Army Command, Ft. Monroe, Va.	17–19
President, Board #1, Headquarters, Continental Army Command, Ft. Sill, Okla.	20
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President, Board #3, Headquarters, Continental Army Command, Ft. Benning, Ga.	22
President, Board #4, Headquarters, Continental Army Command, Ft. Bliss, Tex.	23
Commanding General, U. S. Army Caribbean, Ft. Amador, C. Z. ATTN: Cml. Off.	24
Commander-in-Chief, Far East Command, APO 500, San Francisco, Calif. ATTN: ACofS, J-3	25–26
Commanding General, U. S. Army Europe, APO 403, New York, N. Y. ATTN: OPOT Div., Combat Dev. Br.	27–28
Commandant, Command and General Staff College, Ft. Leavenworth, Kans. ATTN: ALLLS(AS)	29–30
Commandant, The Artillery and Guided Missile School, Ft. Sill, Okla.	31
Secretary, The Antiaircraft Artillery and Guided Missile School, Ft. Bliss, Tex. ATTN: Maj George D. Breitegan, Dept. of Tactics and Combined Arms	32
Commanding General, Army Medical Service School, Brooke Army Medical Center, Ft. Sam Houston, Tex.	33
Director, Special Weapons Development Office, Headquarters, CONARC, Ft. Bliss, Tex. ATTN: Capt T. E. Skinner	34
Commandant, Walter Reed Army Institute of Research, Walter Reed Army Medical Center, Washington 25, D. C.	35
Superintendent, U. S. Military Academy, West Point, N. Y. ATTN: Prof. of Ordnance	36
Commandant, Chemical Corps School, Chemical Corps Training Command, Ft. McClellan, Ala.	37
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Director, Waterways Experiment Station, PO Box 631, Vicksburg, Miss. ATTN: Library 51
Director, Armed Forces Institute of Pathology, Walter Reed Army Medical Center, 6825 16th Street, N. W., Washington 25, D. C. 52
Director, Operations Research Office, Johns Hopkins University, 7100 Connecticut Ave., Chevy Chase, Md., Washington 15, D. C. 53
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Commander, Far East Air Forces, APO 925, San Francisco, Calif. — 105
Commander-in-Chief, Strategic Air Command, Offutt Air Force Base, Omaha, Nebr. ATTN: Special Weapons Branch, Inspector Div., Inspector General — 106
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Commander, Eighth Air Force, Westover AFB, Mass. ATTN: Operations Analysis Office — 144
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Commander, Western Development Div. (ARDC), PO Box 262, Inglewood, Calif. ATTN: WDSIT, Mr. R. G. Weitz — 146

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Director, Weapons Systems Evaluation Group, OSD, Rm 2E1006, Pentagon, Washington 25, D. C. — 149

Armed Services Explosives Safety Board, D/D, Building T-7, Gravelly Point, Washington 25, D. C. 150
Commandant, Armed Forces Staff College, Norfolk 11, Va. ATTN: Secretary 151
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Commanding General, Field Command, Armed Forces Special Weapons Project, PO Box 5100, Albuquerque, N. Mex. ATTN: Technical Training Group 158–159
Chief, Armed Forces Special Weapons Project, Washington 25, D. C. ATTN: Documents Library Branch 160–168

ATOMIC ENERGY COMMISSION ACTIVITIES

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Commander, Operational Development Force, United States Atlantic Fleet, United States Naval Base, Norfolk 11, Va. 210